BELLCOMM. INC.
955 L'ENFANT PLAZA NORTH, S.W.   WASHINGTON, D.C. 20024

B70 03070

SUBJECT: Navigation and Guidance Aspects of
Data Acquisition Requirements for
Planetary Missions - Case 103-7

DATE: March 25, 1970

FROM C. C. H. Tang

ABSTRACT

The purpose of this paper is to assess, prior to
a specific planetary mission, the requirements for navigational
data necessary for a high level of confidence in the success of
the navigation and guidance aspects of the mission.

A range of manned and unmanned missions is reviewed,
including the Grand Tours, to assess these requirements and
the degree to which they can be met by precursor missions.
Unless the accuracy in measuring the speed of light can be
improved drastically, the conventional earth-based radar
ranging cannot improve the accuracies of the ephemerides and
astronomical units any further. Unmanned flyby missions are
effective steps toward improving the accuracies in the deter-
mination of the mass of the target planet and the astronomical
unit. Orbiter missions can improve the accuracy in determining
(a) the target planet gravitational field distribution, (b) the
astronomical unit, (c) the ephemerides of the target planet and
the earth, (d) the target planet radius, and (e) the comprehen-
sive atmospheric profile and composition.

Spacecraft-based approach navigation systems for
unmanned planetary exploration are preferable but not mandatory,
except for certain swingby missions. For manned planetary
missions, the spacecraft-based autonomous approach navigational
system appears to be mandatory in an effort to increase mission
reliability and safety through redundancy.

The spacecraft-based approach navigation system could
be based either on the TV concept of taking target pictures
with a star background or on the celestial navigation concept
of space angle measurements. The accuracy requirement for
celestial angle measurements is roughly six arc seconds (three-
sigma) for outer planet missions and less (about one arc minute)
for Mars and Venus missions.

(CODE)

21

(NASA CR OR TMX OR AD NUMBER)   (CATEGORY)

MEMORANDUM FOR FILE

I. INTRODUCTION

The purpose of this paper is to assess, prior to a
specific planetary mission, the requirements for navigational
data necessary for a high level of confidence in the success
of the navigation and guidance aspects of the mission.

For the Apollo mission, the deep space network (DSN)
tracking system utilizing a coherent two-way doppler link be-
tween the earth and the spacecraft is adequate. For certain
planetary missions, the accuracy of spacecraft navigation may
play a key role in mission success. The earth-based doppler
tracking system alone may not meet the navigation requirements
of certain missions to outer planets, mainly because of the
present uncertainties in ephemerides and physical constants
and the tracking station time signal drift over the long round-
trip signal transmission delay. Radar ranging of the inner
planets together with the information obtained from completed
missions to Venus and Mars have made their positional uncer-
tainty negligible for navigation purposes. On missions to
outer planets it appears, however, that a supplementary navi-
gation system in addition to the earth-based DSN navigation
system may be desirable, because (1) direct radar ranging to
outer planets is at present impractical due to the large dis-
tances and the unknown but presumably strong atmospheric
absorption,[1] (2) the positional uncertainties of the outer
planets increase at a rate proportional to the distance between
the earth and planet.

Earth-based navigation can yield accurate information
on the position of a spacecraft relative to the earth, but the
accuracy of the position of the planet with respect to the earth
is limited by the uncertainties of the physical model of the
solar system. The position of a spacecraft with respect to
the planet is therefore also limited by the planetary position
uncertainties if an earth-based navigation system alone is used.
One way to circumvent the uncertainty in the actual position of
a target planet is to use some kind of supplementary spacecraft-
based navigation relative to the target planet. The purpose of
switching the navigation reference point from the Sun or earth

to the target planet during the approach phase (defined here as the transition phase between the heliocentric transfer ellipse and target planet hyperbola) is to eliminate the navigation errors due to the uncertainties in the astronomical unit and the ephemeris of the planet. In addition, the switching of the reference point also removes the errors due to imperfect velocity corrections and the perturbation errors due to the long-term solar pressure and attitude control system leaks during the long heliocentric phase. In an attempt to achieve an orderly comparison scheme in data acquisition requirements for all types of planetary missions we first classify unmanned missions into (1) flyby, (2) orbiting, (3) targeting or landing, and (4) swingby. The differences in requirements for manned and unmanned missions will then be discussed.

II.   DATA ACQUISITION REQUIREMENTS COMPARISON

(1)   Flyby Missions:

A conservative estimate of the DSN navigation accuracy in the 1970's is in the neighborhood of 10^{-4} m/sec for range-rate (at one sample per minute) and 10m for range. The earlier flyby missions to Venus and Mars, Mariner II and IV, delivered the spacecrafts within a few thousand kilometers of the aiming points. Recent radar ranging of the inner planets and postflight analyses of DSN tracking data of previous planetary flyby missions have decreased the position uncertainties of the inner planets to the order of of 10 km. It was expected that the Mariner Mars 69 flyby spacecrafts would be delivered within a 100 x 250 km (3-sigma) ellipse[2] of the target aim point (the impact parameter), without the use of spacecraft-based measurements*. If the anticipated one-sigma uncertainties in the A.U. and the ephemerides are, respectively, 100 km and 0.3 arc sec, the axes of 3-sigma dispersion ellipsoids at the target aim point during oppositions for outer planets are approximately as shown in Table I.

Preliminary studies[3-4] appear to indicate that a direct flyby mission of a first generation probe for precursory exploration of Jupiter, Saturn, Uranus, or Neptune can be conducted with the earth-based navigation and guidance alone if dispersions of the order indicated on Table I can be tolerated.

---

*Preliminary JPL post-flight analyses indicate that a one-sigma dispersion ellipse of 70 x 170 km is obtained by using the tracking data between five-day before encounter and four-hour before encounter.

In a flyby mission it is theoretically possible to reduce the size of error dispersions without the aid of space-craft-based measurements at the expense of increasing the ratio of corrective fuel loading to total payload. The extra correc-tive maneuver capability will bring the spacecraft closer to the prescribed periapsis vector by using the earth-based doppler navigation data obtained during the period when the spacecraft enters into the early target encounter phase (defined here as the region from the vicinity of impact point* to periapsis). The earth-based doppler navigation data during the heliocentric phase and the approach phase of the trajectory do not yield significant information on the actual location of the target planet, whereas those during the encounter phase of the trajectory do. Because the significant bending effect of the target planet on the spacecraft trajectory during the encounter phase causes rapid velocity changes, the partial derivatives of the range-rate with respect to the orbit parameters begin to show large variations and therefore contain a large information content for orbit determination. The accuracy of navigation information with respect to the target planet thus gradually increases as the spacecraft comes closer to the target planet during the early encounter phase. The improvement in the navigation information during the period enables guidance calculations to prescribe the necessary corrective maneuver to accomplish the desired terminal trajectory. However, because of the late application of the corrective maneuver in the vicinity of the target planet the propellant requirements become excessive. In an attempt to avoid these excessive fuel requirements, some kind of supplementary spacecraft-based navigation system is desirable in determining during the approach phase the actual location of the target planet with respect to the spacecraft. Such a spacecraft-based autonomous approach navigation system should reduce fuel require-ments for corrective maneuvers substantially, and practically independent of the magnitude of ephemeris uncertainty, if maneu-vers can be applied during the approach phase.

An analytical comparison of earth-based doppler navigation and spacecraft-based navigation was generated[5] for a Mars mission and the curves of Figure 1 represent one axis of the error ellipsoid for the three indicated situations. It is seen that during most of the trip spacecraft-based navigation would prove inferior to earth-based navigation by a factor of fifty (note that spacecraft-based navigation instruments used in the simulation have one-sigma accuracies on the order of a minute of arc and increasing the accuracies of the instruments should reduce the factor). Yet at a half-day from encounter, a cross-over takes place and spacecraft-based navigation is better than earth-based navigation.

---

*Interpreted here as the intersection of the actual trajectory with the line in the direction of the impact parameter, which is the closest distance between the planet and the asymptote.

We conclude that it is desirable for future close flyby missions to outer planets to have a spacecraft-based navigation system if its weight is comparable or less than the weight of propellant to be saved. In addition to possible total payload saving, the use of spacecraft-based navigation also increases overall probability of mission success. The choice of such a spacecraft-based approach navigation system will be discussed later.

An uncertainty in the target planet mass will result in a corresponding change in the angle θ between the approach and departure asymptotes of the target encounter hyperbola. The change $d\theta$ can be expressed by the following relation:

$$d\theta = \frac{2b}{V_\infty^2} \cdot \frac{d\mu}{\mu^2 V_\infty^{-4} + b^2}$$

where b is the impact parameter,
  V_∞ is the asymptotic velocity of the target encounter hyperbola, and
  μ is the gravitational parameter.

This relation is shown parametrically in Figure 2 for Mars, Figure 3 for Jupiter, and Figure 4 for Saturn for mass uncertainties shown in Table I.

Since one of the scientific objectives of planetary flyby missions is to improve the accuracies of the mass of the target planet and the astronomical unit, flyby missions thus can aid this important navigational aspect of data acquisition for subsequent orbiter missions. The improved mass value increases the probability that an orbiter will be inserted into a prescribed orbit without carrying excessive trim propellant.

In passing we mention that the accuracies of the mass determinations of Venus and Mars have been improved by two to three orders of magnitude through analyses of Mariner series navigation measurements. The best estimate of the mass of Venus in 1961 was 408,7000±1000 in units of mass reciprocal and is presently 408,522±3 and that of Mars in 1961 was 2,090,000±10,000 and is presently 2,098,700±100. It is expected that Mariner VI and VII will improve the Mars mass accuracy by another order of magnitude. Future flyby missions to Mercury and outer planets are expected to yield similar improvement in their mass values. Although the planetary radar bounce delay time is one of the most precisely determined quantities and has an estimated accuracy

of 15μ sec[6] for one astronomical unit, its conversion to
length units depends critically on the accuracy of the speed
of light, which has an estimated accuracy about one part in
a million. Unless the accuracy in measuring the speed of
light can be improved drastically,* or planetary orbiter
missions are carried out, the accuracy of the astronomical
unit will remain in the 100-200 km range.

    (2) Orbiter Missions:

    Orbiter missions are more complex than flyby missions
because of orbit insertion propellant loading and stringent
navigation and guidance requirements. Typically one-half of
the weight[3] injected from the earth will be used for the
planetary orbit insertion propulsion system. The navigation
and guidance requirements of a planetary orbiter mission dic-
tate that, to achieve a desired orbit, correct insertion maneu-
vers be performed at prescribed locations, such as the periapsis
of the encounter hyperbola, in order to avoid excessive trim
propellant.

    Evidently an orbiter mission is capable of performing
all the scientific objectives (relative to the target planet)
of a single-pass flyby mission and much more. From the point
of view of trajectory design, navigation, and guidance, the
important contribution of planetary orbiter missions is in
improving the accuracy of (a) the gravitational field distri-
bution of the target planet, (b) the astronomical unit in abso-
lute length, (c) the ephemerides of the earth and the target
planet because of the relative velocity motions between the
earth-centered observer and the target-planet-centered orbiter,
(d) the target planet diameter through repeated occultation
experiments, (e) the comprehensive atmosphere profile and
composition through repeated occultation experiments. An
accurate knowledge of the planet radius is important for space-
craft-based optical celestial navigation measurements. It is
noted that items (a) through (e) assumes that the orbit param-
eters of a planetary orbiter can be determined within a few
days of tracking using the present DSN capabilities. Recent
study[7] indeed shows that this can be done.

    The accuracy in measuring the mass of the target planet
cannot be improved by means of a planetary orbiter and this is
also verified in a recent study[7]. This is mainly due to the
fact that the mass and semi-major axis of an elliptical orbit are
highly correlated through the energy equation. This is why the

---

    *Experiments are now under way that are expected to improve
the accuracy by at least two orders of magnitude.

earth mass value is determined by lunar and planetary probes and not by earth satellites which yield information on earth gravitational field harmonics.

Because of the continuing improvement in the accuracies of the astronomical unit and of masses of Mars and Venus through the combination of radar bouncing measurements and the Mariner series missions, a planetary orbiter to Mars or Venus will likely be inserted close to the prescribed orbit without either carrying excessive trim propellant or the use of a space-craft-based approach navigation system. Dixon[3] cites preliminary results indicating that entry into Jupiter orbit could be accomplished by the earth-based navigation system alone, for an orbit of 1.5 radii (periapsis) x 35 radii (apoapsis) with 3-sigma uncertainty of 0.1 and 0.4 radii, respectively. It is probable that orbiter missions to Mercury or the outer planets may need a supplementary spacecraft-based approach navigation system as a trade-off for reducing corrective fuel loading to insert the orbiter into a prescribed orbit.

(3) Landing Missions

On the assumption that through planetary flyby and orbiter missions the navigational data acquisition requirements (accuracies of the gravitational field, astronomical unit, ephemerides, mass, radius, and atmospheric profile and composition) are satisfied, successful soft landing within a prescribed region on a planet can be achieved. This requires, however, the aid of a proper spacecraft-based descent navigation and guidance system, provided the atmospheric model of the target planet is reasonably defined from the long-term results of the previous orbiter measurements.

From the trajectory point of view there can be three modes of landing. The first mode is to land a spacecraft directly on a target planet via a hyperbolic flyby landing path, with "vacuum" periapsis less than the target planet radius. This is essentially the Ranger or Surveyor type of landing on a planet, taking into account the atmosphere of reasonably defined properties. The second mode is to inject a landing probe from a hyperbolic flyby spacecraft, and the third mode is to inject the landing probe from the spacecraft after the spacecraft is inserted into a planetary orbit. The choice of a particular mode depends on the overall mission objectives and propulsion weight tradeoffs. Since the location of the spacecraft with respect to the target planet can be more precisely determined for an orbiting spacecraft than for a single-pass flyby spacecraft, it is expected that a soft landing probe injected from an orbiter can reach a prescribed region on the target planet with better precision. In addition,

the excess velocity above the planetary capture limit is already removed by deboosting the orbiter into orbit so that the probe velocity which must be removed by either aerodynamic or retro-braking has been substantially reduced to simplify the landing approach. The spacecraft-based or probe-based descent navigation and guidance system to land the probe within the prescribed region on the target planet might be similar in concept to that of the Apollo Lunar module landing, except where the "vacuum" entry must be replaced by an atmospheric entry.

(4) Swingby Missions:

Swingby missions usually refer to those missions in which a spacecraft utilizes the gravitational perturbation of an intermediate planet during flyby to reshape its trajectory in order to reach a third planet, whereas a flyby mission aims to pass only by one target planet. Launch vehicle energy requirements increase rapidly as direct ballistic flights pass outside Mars' orbit or inside Venus' orbit. Thus high launch energies are required for flights to either Mercury or Jupiter. For missions to Mercury or beyond Jupiter, swingby (gravity-assisted) trajectories appear most attractive. For example, in 1973 a mission to Mercury via a close encounter with Venus is a swingby mission reducing launch energy by about 50% ($C_3=V_\infty^2/2$ of about 18 km^2/sec^2 instead of 42 km^2/sec^2 for minimum energy direct flight of comparable flight time).

Because of its relatively small mass with respect to Jupiter, Mars is of little or no help for gravity-assisted missions requiring short flight time to Jupiter. On the other hand, due to its relatively large mass, Jupiter can be very attractive for gravity-assisted missions to Saturn and/or other outer planets. For missions beyond Jupiter, the significant advantage of swingby missions when compared with direct ballistic missions are: (a) flight time can be drastically reduced and (2) through efficient trajectory design launch energy requirements are not substantially greater than those to reach Jupiter alone. As shown in Figure 4,[7] for example, flight time to Saturn via a 1978 Jupiter swingby amounts to about 50% (from 6.1 years to 3.3 years) of the direct transfer time for the minimum launch energy C_3 of 109 km^2/sec^2, and that to Neptune via a 1979 Jupiter swingby amounts to only about 25% (from 30.7 years to 7.7 years) of the direct transfer time for the minimum energy of 135 km^2/sec^2. Alternatively, for the same transit time of of about 6 years, launch energy can be reduced from 157 km^2/sec^2 for

Uranus direct transfer to 115 km^2/sec^2 for a 1979 Jupiter swingby to Uranus. Other possible comparisons can also be obtained from Figure 5. Multiple target trajectories such as the Earth-Jupiter-Saturn-Uranus-Neptune "grand tour" can be completed in a Jupiter swingby flight of about 8.5 years for a launch energy of about 130 km^2/sec^2 or about 12 years for a launch energy of about 90 km^2/sec^2.

Spacecraft energy gain (or loss) during swingby is the result of the work done on the spacecraft by the gravitation field of the intermediate planet moving relative to the inertial heliocentric coordinate system. The heliocentric energy of the spacecraft may be increased (or decreased) when the spacecraft passes from the trailing-edge (or leading-edge) of a planet. When the angle between the planet's velocity vector and the pericenter direction is larger than ± $\pi/2$, the spacecraft makes a trailing-edge passage of the planet and gains energy.

For certain swingby missions a spacecraft-based approach navigation system appears to be necessary. The rings of Saturn lie within the Roche limit (2.46 Saturn radii) and consist of many small particles orbiting in the equatorial plane of Saturn. Three rings, extending approximately from 1.2 to 2.4 Saturn radii, are noted and these rings should be avoided in flight paths. For detailed observation of Saturn, a spacecraft must pass between Saturn and the inner ring. To obtain a crude idea of propellant requirement comparison between a mission with the earth-based navigation system alone and that supplemented by a spacecraft-based navigation system, Kingsland[9] presented in Table 2 a comparison of propellant requirements for typical Grand Tour Missions to be launched in 1977 and 1978 and in Table 3 a set of typical maneuvers for an interior mission to be launched in 1977. Exterior ring missions would result in more distant planetary approaches and smaller flyby bending angles and thus produce a lesser magnification of position and velocity errors. As a result, exterior missions will be less critical from the point of view of navigation accuracy requirement and thus require smaller maneuver propellant as shown in Table 2. The use of supplementary spacecraft-based optical navigation could reduce maneuver propellant requirements drastically, especially for the inner ring missions as shown in Table 2. In order to correct for the accumulating effect of various small errors in spacecraft guidance and to maintain navigation accuracy within allowable limits, it will be necessary to perform corrective maneuvers shortly after departing each planet and shortly before arriving at the next planet as shown in Table 3. Friedlander's estimates[10]

for the 1977 mission are fairly close to Kingsland's. The
post-encounter maneuvers are performed to eliminate the errors
resulting from inaccuracy in estimating the gravitational
deflection due to the mass of the encounter planet. Because
of the utilization of the intermediate planet gravity-assist,
the post-encounter trajectory is very sensitive to encounter
position errors of the spacecraft with respect to the inter-
mediate planet. To achieve the desired near-encounter position
at the next planet, it is necessary to control precisely both
the encounter and post-encounter trajectory at the preceding
planet. With a spacecraft-based approach navigation system, the
necessary guidance maneuvers both before and after each planet
encounter could be performed much earlier with much smaller,
and therefore efficient, fuel expenditure. It is clear, however,
that the significant advantages of the Grand Tour are obtained
at the expense of increased navigation accuracy requirements.

It can therefore be said that a supplementary spacecraft-
based approach navigation systems is necessary for certain swingby
missions to outer planets and is highly desirable, if not necessary,
for direct transfer to an outer planet. Preferably any adopted
spacecraft-based approach navigation system should be included in
the first Jupiter flyby mission in order to field-test the system.

Because of its extremely large mass and its relatively
large distance from the Sun, the radius of the sphere of influence
of Jupiter is about 50 million kilometers or one-third of one A.U.
The dominant transition region between the Sun and Jupiter extends
about 50-100 million kilometers whereas that between Sun and Mars
or Venus is almost negligible. Accordingly the three-body effect
on a spacecraft in the transition region is much more pronounced
in the case of Jupiter than in the case of Mars, or Venus, and
any spacecraft-based navigation and guidance computation for outer
planet missions must be based on three-body formulation, not on
patched conic type two-body formulation.

Spacecraft-Based Approach Navigation System

Possible spacecraft-based approach navigation and
guidance systems to be used during the approach phase to a planet
include (A) radar ranging from the spacecraft to the planet,
(B) television pictures of the target planet with star background
pattern, and (C) celestial optical measurements of spacecraft-
centered angles between two reference features.

Because of the unknown state of planetary features and
other limitations, the radar ranging method will not be considered
here. In the TV navigation concept, television pictures of the
target planet are taken with the field of view large enough to

include a star pattern background. The position of the target
planet image on the screen relative to the star pattern image
defines the direction of the target planet in inertial space.
A visual image system capable of detecting the planet disc and
fourth magnitude stars is expected to achieve a nominal 3-sigma
planet-center-finding error of 1/3% of the angular diameter of
the planet[2]. It is probable that TV requirements for locating
the target planet can be made compatible with approach science
TV requirements. The TV pictures are transmitted to the earth
for analysis. This requires, however, a relatively large amount
of transmitted data, and some form of data compression may be
needed. It is evident that the images of the natural satellites
of a planet can also be used to determine the direction of the
center of the mother planet[11]. Star images in TV frames con-
taining natural satellite images of a planet would yield a precise
estimate of the pointing direction to the planet.

The optical measurements from the spacecraft may com-
prise basically a sequence of angle measurements between two
reference features. The angle between the Sun (or $Star_1$) and
the planet is the cone angle and the angle between the Sun (or
$Star_1$)-spacecraft-planet plane and the Sun (or $Star_1$)-spacecraft-
$Star_2$ plane is the clock angle. The center of the planet can be
located by two star-(planetary) horizon measurements on opposite
sides of the planet (thus the angle subtended by the planet also)
or by a planet center-finding device such as the planet tracker-
scanner. Note that the cone and clock angles are analogous to
colatitude and latitude, respectively, on the celestial sphere
with the Sun at the pole. The cone and clock angle measurements
provide information about the position deviation perpendicular
to the direction of the target planet sighted, whereas the
angular diameter measurements provide information about position
deviation in the direction of the target planet.

In the spacecraft-based navigation procedure an appro-
priate schedule of angle measurements is made during the approach
phase and, in order to continuously take advantage of the most
recent "best estimate" in predicting observations, the Schmidt-
Kalman recursive filtering technique instead of the least square
batch filtering technique is used to process the orbit determi-
nation information. At each observation, the estimated value
of the measured quantity is determined from the present estimate
of the position and velocity of the spacecraft and is compared
with the measured value. A revised estimate of the position
and velocity is calculated as a linear function of the dif-
ference between the estimated and measured values. The actual
computation can be done either by the spacecraft computer, if
available, or with earth-based computing facilities.

Studies[12-14] have shown that increasing the measurement density of angles has a similar effect as decreasing the noise in measurements. Instrument biases may be estimated simply as additional system parameters. The angle biases initially degrade the accuracy in determining the orbit parameters, but increasing the number of measurements to sufficient extent yields also accurate estimates of these biases. Accordingly the system soon becomes relatively insensitive to the initial uncertainties in the biases. The controlling error appears to be the planet center-finder error as a percent of the planet angular diameter. It has, however, been shown[2] that when the earth-based navigation measurements are supplemented by spacecraft-based celestial optical measurements during a Grand Tour Mission, there is little advantage in improving the center-finding accuracy beyond the 1% level.

In an attempt to get a rough idea of the required pointing accuracy of a space sextant or planet tracker, reference can be made to the previously mentioned 3-sigma ephemeris uncertainty of 3000 km for the case of Jupiter. Let us assume that the resultant miss uncertainty of the earth-based orbit determination for the Jupiter mission is about 2 x 3000 km. Let us also assume that the first angular measurement be made at a distance of about twice the radius of sphere of influence, which for Jupiter is about one hundred million kilometers. This means that, to be equivalent to the DSN accuracy, the first angular measurement must be accurate to $\frac{6000}{100 \times 10^6}$ radian, or about twelve arc sec (3-sigma). This accuracy improves, as the spacecraft approaches closer to the planet. As the number of measurements accumulates, the Schmidt-Kalman filtering process can improve the orbit parameter estimation accuracy. Similar analysis for other outer planets shows a slightly relaxed accuracy requirement; namely, 20 arc sec for Saturn, 50 arc sec for Uranus and Neptune. To obtain a significant improvement over the DSN, the spacecraft-based angular measurement accuracy should be better than twelve arc sec, say, by a factor of two. Accordingly, six arc sec (3-sigma) appears to be the adequate and practical accuracy requirement for spacecraft-based approach navigation devices to be used on outer planet missions. Similar analysis for Mars or Venus missions indicates that the accuracy requirement is roughly an order of magnitude lower (1 arc minute) than that for outer planet missions. A sample comparison of the earth-bound navigation and spacecraft-based celestial navigation is shown in Figure 6[10] for the Uranus approach of the 1977 inner ring Grand Tour. The spacecraft-based celestial instrument is assumed to have a three-sigma accuracy of six arc sec and measurements are made at the rate of one every two hours. The a priori instrument bias is 200 arc sec and the a priori planet center-finder bias is 1/3% planet diameter.

Flander, et al,[15] report that an automatic "Sextant" navigation instrument with two lines of sight which simultaneously view two navigation reference targets is reported to be capable of 20 arc sec (one-sigma) accuracy, and another automatic sextant-type instrument is estimated to be capable of 3 arc sec (one-sigma) accuracy. He also reports that a sequential instrument (utilizing a scanner photometer mated to a ring laser) which has one line of sight that first locates one target and then rotates to locate the second target, has an anticipated accuracy of about 1 arc sec (one-sigma).

It is clear that angle measurement uncertainties limit the navigation accuracies achievable. From the simulation results[12-16] the following conclusions can be drawn:

(1) For a given measurement schedule, the navigation accuracy during the approach phase is approximately proportional to the angle measurement accuracy and is essentially independent of ephemeris and astronomical unit uncertainties.

(2) For uncorrelated measurement uncertainties, an improvement in navigation accuracy during the approach phase can be obtained simply by increasing the number of measurements.

(3) The fuel required for correction maneuvers during the approach phase to achieve a prescribed guidance accuracy at the target planet is approximately proportional to the angle measurement uncertainty. More accurate angle measurements enable earlier and more accurate correction maneuvers and thus a considerable reduced total fuel expenditure for correction maneuvers.

(4) Landmark tracking through optical angle measurements is a useful navigation technique when the spacecraft is in the encounter phase with the target planet or is orbiting the target planet.

Manned Missions

For manned missions, subsystem redundancy becomes a prime requirement in order to insure significantly improved mission reliability. In addition to the need of life support systems for manned missions, the obvious major difference between a manned and unmanned mission of any type (flyby, orbital, landing or swingby) is that a successful manned mission must include a return trip. Because of the long duration of the round trip for a planetary manned mission, long-term redundancy reliability is mandatory. The measure of success of an unmanned mission is generally judged by the quantity and quality of

recovered data. Thus if communication with an unmanned space-
craft is lost, continued functioning of the navigation, guidance,
and control system is no longer relevant. Accordingly for an
unmanned spacecraft the navigation system does not require a
significantly greater reliability than the remainder of the
payload. For a manned mission, however, higher reliability
must be imparted to the life supporting systems and spacecraft-
based navigation system in order to increase the probability
of a safe return trip. This implies then that the spacecraft-
based autonomous approach navigation system becomes a mandatory
redundancy navigation system for manned planetary missions.

Conclusions

        In an orderly exploration of planets, the data acqui-
sition requirements for navigation and guidance indicate that
unmanned flyby missions to a target planet are effective steps
toward improving the accuracies of the mass of the target planet
and the astronomical unit. Because of these improved accuracies,
a subsequent orbiter mission will have an increased probability
of inserting an orbiter into a prescribed orbit without carrying
excessive trim propellant. Orbiter missions are expected to
supply the following important improvements in the accuracy of
(a) the target planet gravitational field distributions, (b) the
astronomical unit, (c) the ephemerides of the target planet and
the earth, (d) the target planet radius, and (e) the comprehen-
sive atmospheric profile and composition. In fact items (a)
through (e) are the navigation data requirements for subsequent
landing missions. With the aid of the spacecraft-based descent
navigation and guidance system, landing within a prescribed
location can be achieved after orbiter missions have obtained
accurate information about items (a) and (e) above.

        A spacecraft-based approach navigation system for
unmanned planetary exploration is preferable but not mandatory
except for swingby missions. For certain swingby missions the
use of spacecraft-based approach navigation system can reduce
the ΔV guidance requirements by factor of two to four. The
spacecraft-based approach navigation system could be based on
either the TV concept of taking target planet pictures with a
star pattern background or the celestial navigation concept of
space angle measurements. The requirements in identifying the
target planet position with respect to star pattern background
(or its natural satellite background) probably can be made
compatible with approach science TV requirements. The accuracy
requirement for celestial angle measurements is in the neighbor-
hood of six arc sec (three-sigma) for outer planet missions.

For manned planetary missions, the spacecraft-based approach navigation system appears to be mandatory in an effort to increase mission reliability through redundancy.

C. C. H. Tang

1014-CCHT-jf   C. C. H. Tang

Attachments
  References
  Tables I-III
  Figures 1-6

NOTE: After the completion of this memorandum, a paper entitled, "Guidance and Navigation Requirements for Missions to the Outer Planets" by L. A. Manning of OART and D. C. Fraser of MIT was presented at the AIAA 8th Aerospace Sciences Meeting, New York, New York, January 19-21, 1970. The results of this memorandum are in substantial agreement with those of the paper.

BELLCOMM, INC.

REFERENCES

1. Evans, J. V. and Hagtors, T., Radar Astronomy, p. 300, McGraw Hill, 1968.

2. Hamilton, T. W., "Earth-based Navigational Capabilities for Planetary Missions," Paper-68-852, AIAA Guidance Control, and Flight Dynamics Conference, August, 1968.

3. Dixon, W. J., "Major System Design Problems for Deep Space Probes," Journal of Spacecraft and Rockets, Volume 4, pp. 1121-1127, September, 1967.

4. Mathews, H. R. and Hall, C. F., "The Pioneer Mission to Jupiter," Paper-69-99, American Astronomical Society 15th Annual Meeting, June 17-20, 1969.

5. Moscowitz, S., "Optical Guidance and Navigation Instrumentation for Manned Space Flight," pp. 149-179, Proceedings of the ION National Space Meeting on Simplified Manned Guidance, Navigation, and Control," February 19-21, 1968.

6. Melbourne, W. G., Mulholland, J. D., Sjogren, W. L., and Storms, F. M., Jr., "Constant and Related Information for Astrodynamic Calculations, 1968," TR-32-1306, JPL, Pasadena, California, 1968.

7. Tang, C. C. H. and Greer, C. L., "Determination of Orbits of Planetary Artificial Satellites and Planetary Gravitational Fields," AIAA Journal, Volume 7, pp. 1468-1476, August 1969.

8. Eckman, P. K. and Parks, R. J., "Spacecraft for Deep Space Investigation," Paper 68-1979, AIAA 5th Annual Meeting and Technical Display, October 21-24, 1968.

9. Kingsland, L., Jr., "Trajectory Analysis of a Grand Tour Mission to the Outer Planets," Paper 68-1055, AIAA 5th Annual Meeting and Technical Display, October 21-24, 1968.

10. Friedlander, A. L., "Guidance Analysis of the Multiple Outer Planet Mission," Paper 69-105, AASS/AIAA, Astrodynamics Specialist Conference, September 3-5, 1968.

11. Durbury, T. C., "Spacecraft Navigation Using Science Television Data," American Geophysical Union Annual Meeting, Washington, D. C., April 22-24, 1969.

BELLCOMM, INC.

12. Gate, C. R. and Gordon, H. J., "Planetary Approach Guidance," *Journal of Spacecraft*, Volume 2, 1965, pp. 160-166.

13. Seaman, L. T. and Brown, H. E., "Planetary Approach Guidance for a Martian Mission," American Astronautical Society, Proceedings - 1967, Paper AAS-67-453 (GC-3).

14. Hartwell, J. G., Dauby, J. M. A., and Jones, A. L., "Planetary Approach Navigation," Journal of the Institute of Navigation, Volume II, Summer, 1967, pp. 125-144.

15. Flanders, J. H., Fraser, D. C., and Lawson, J. R., "Technology for Guidance and Navigation of Unmanned Deep Space Missions in the 1970's," Paper 68-1104, AIAA 5th Annual Meeting, October 21-24, 1968.

16. Apollo Staff, "Control, Guidance and Navigation for Advanced Manned Missions," Volume III, MIT Instrumentation Laboratory Report, R-600, January, 1968.

TABLE I

Dispersion Ellipsoid

	Jupiter	Saturn	Uranus	Neptune
* Radius (km)	71,372.0	60,401.0	23,535.0	22,324.0
* Mass reciprocal	$1,047.3908\pm0.0074$	$3,449.2\pm0.4$	$22,930\pm6$	$12,960\pm100$
* Semi-major axis (A.U.)	5.2026554	9.5226887	19.163719	30.068940
3-σ (km) dispersion ellipsoid (axial x transverse)	1,200 x 3,000	2,500 x 6,000	5,5000 x 13,000	8,700 x 20,000

*Melbourne, W. G., et. al., "Constants and Related Information for Astrodynamic Calculations, 1968," JPL Technical Report 32-1306, 1968.

TABLE II

Mean Plus Three Sigma Maneuver Requirements, m/sec

	1977		1978	
	Interior Ring	Exterior Ring	Interior Ring	Exterior Ring
Doppler Only	1858 (54.6%)[a]	610 (22.9%)	1095 (37.2%)	478 (18.4%)
Doppler & Optical	317 (12.6%)	238 (9.6%)	276 (11.1%)	229 (9.3%)

[a] Propellant fraction of spacecraft, assuming I_{sp} = 240 sec

TABLE III

Midcourse Maneuvers, 1977 Grand Tour, Interior Ring Passage

Maneuver	Doppler Only		Doppler & Optical	
	Time	rms Size (m/sec)	Time	rms Size (m/sec)
Post-Earth	I +10 days	18.1	I +10 days	18.1
1st Pre-Jupiter	E -24 days	3.2	E -18 days	4.3
2nd Pre-Jupiter	E -5 days	3.3		
Post-Jupiter	E +20 days	13.5	E +20 days	9.8
1st Pre-Saturn	E -18 days	3.8	E -9 days	7.0
2nd Pre-Saturn	E -2 days	17.9		
Post Saturn	E +20 days	210.2	E +20 days	63.5
1st Pre-Uranus	E -24 days	62.2	E -30 days	21.3
2nd Pre-Uranus	^{a}E -15 hr	140.8	E -9 days	8.2
Post-Uranus	E +20 days	553.0	E +20 days	41.2
Pre-Neptune	E -100 days	32.9	E -100 days	16.9
Total rms size		1059.0		190.2
Mean + 3-sigma		1857.5		316.5

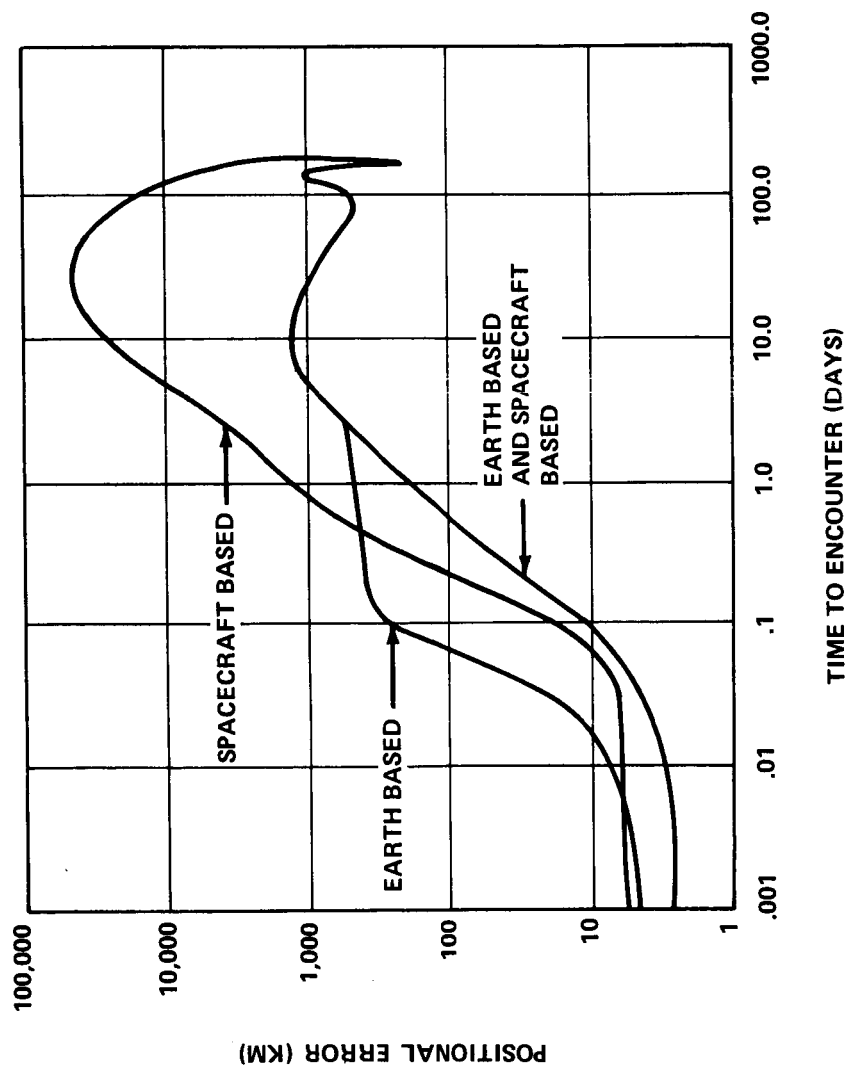[a]Based on data up to E -20-hr with 5-hr round trip signal transmission time

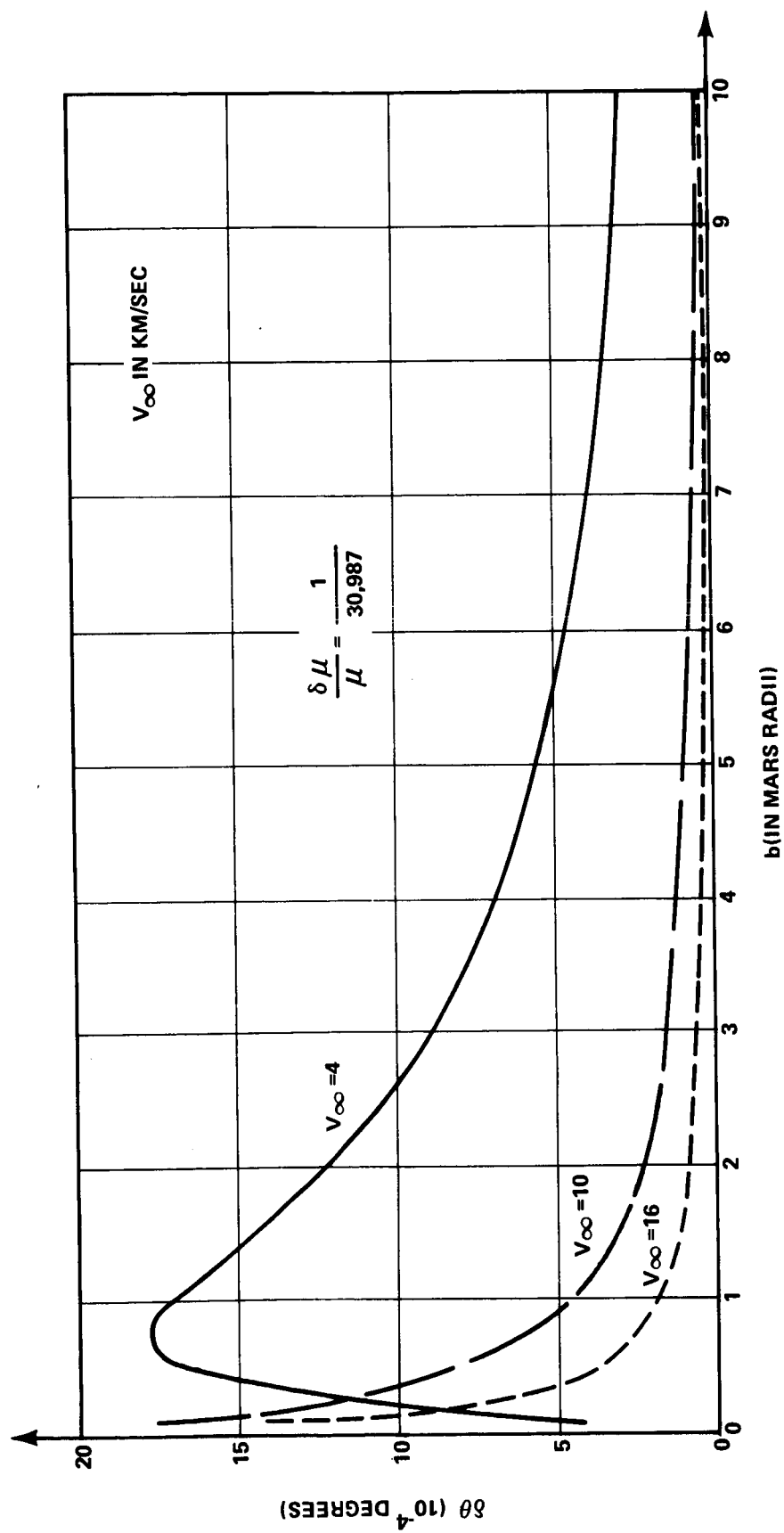FIGURE 1. VEHICLE POSITIONAL ACCURACIES FOR FLIGHT TO MARS

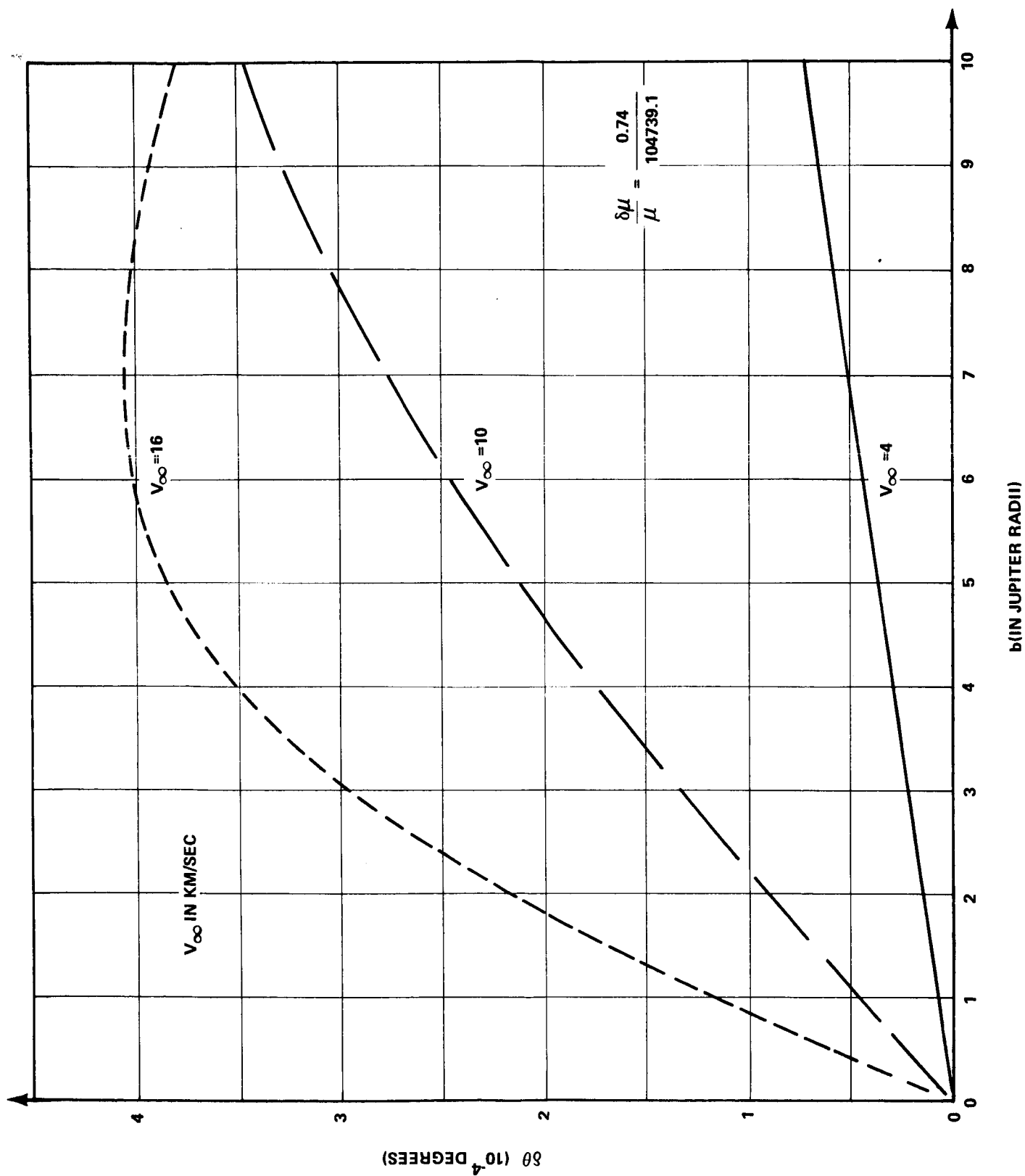FIGURE 2 - $\delta\theta$ VERSUS IMPACT PARAMETER b FOR MARS

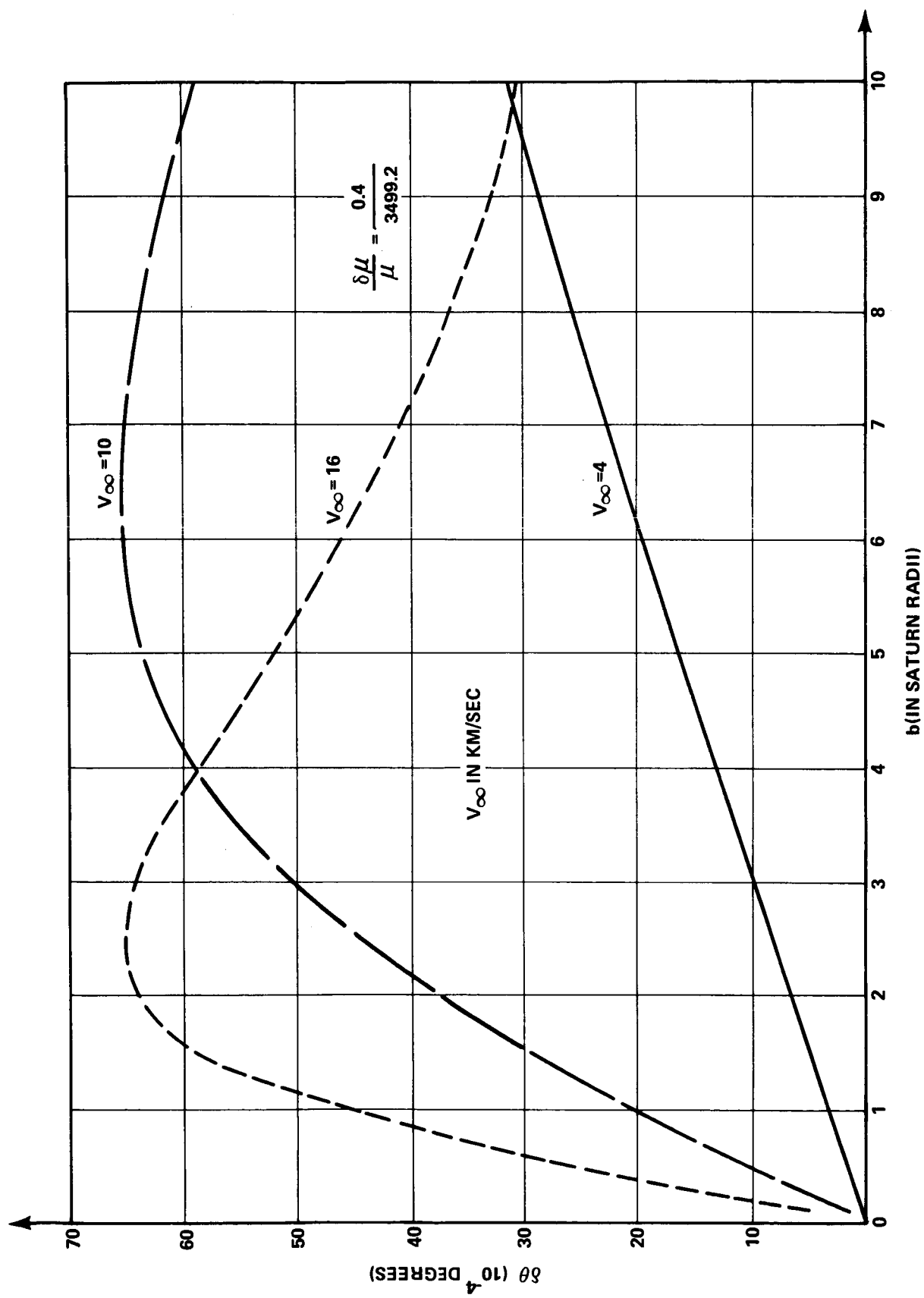FIGURE 3 - $\delta\theta$ VERSUS IMPACT PARAMETER b FOR JUPITER

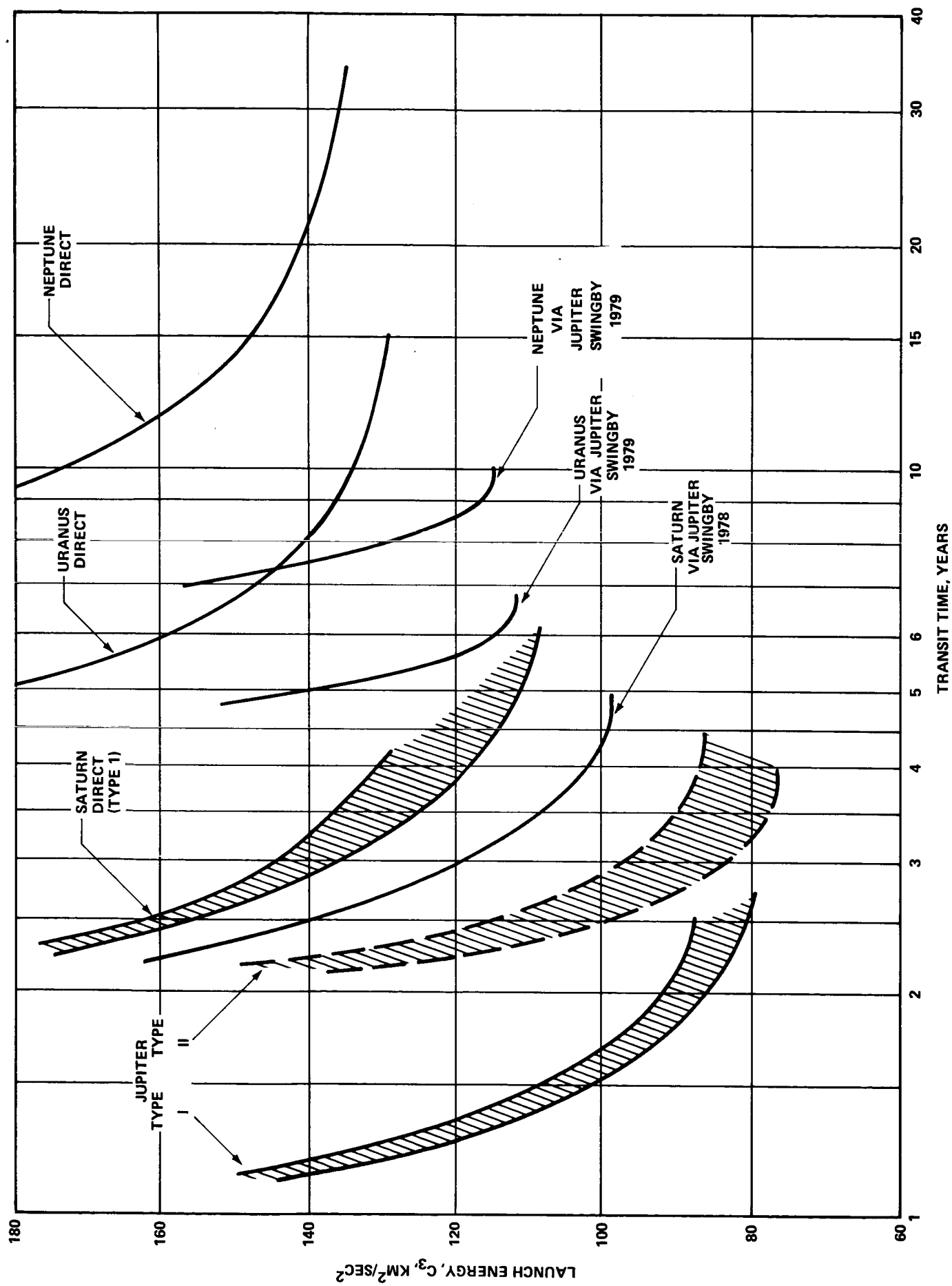FIGURE 4 - $\delta\theta$ VERSUS IMPACT PARAMETER b FOR SATURN

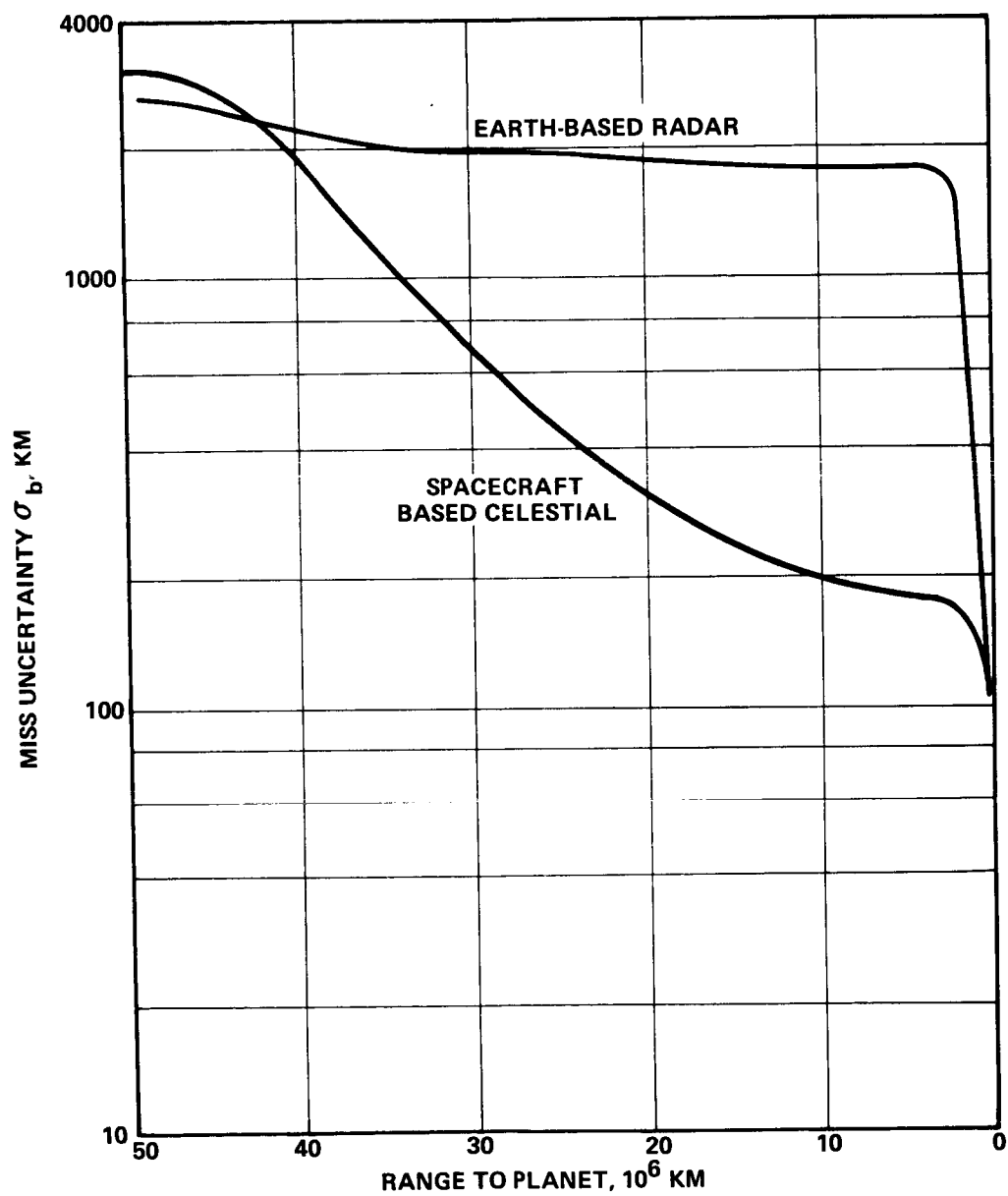FIGURE 5¹. COMPARISONS BETWEEN DIRECT BALLISTIC AND GRAVITY - ASSISTED TRAJECTORIES

FIGURE 6 - MISS UNCERTAINTY FOR URANUS APPROACH ORBIT DETERMINATION, 1977 - INNER RING GRAND TOUR.

BELLCOMM, INC.

Subject: Navigation and Guidance Aspects of Data Acquisition Requirements for Planetary Missions Case 103-7

From: C. C. H. Tang

Distribution List

NASA Headquarters

W. O. Armstrong/MTX
P. E. Culbertson/MT
C. J. Donlan/MD-T
E. W. Hall/MTG
T. A. Keegan/MA-2
R. Kraemer/SL
R. L. Lohman/MF
D. R. Lord/MTD
A. D. Schnyer/MTV
J. W. Wild/MTE

Manned Spacecraft Center

J. H. Boynton/PT8
C. Covington/EW2
D. E. Fielder/HC
G. C. Miller/EW31
M. A. Silveira/EX
J. M. West/AE

Marshall Space Flight Center

W. R. Lucas/PD-DIR
R. J. Harris/PD-SA-P

Kennedy Space Center

J. P. Claybourne/DE-FSO
R. C. Hock/AA
N. Salvail/DE-FSO

Langley Research Center

W. R. Hook/156
N. L. Crabill/159

Ames Research Center

J. S. White/FST

Jet Propulsion Laboratory

T. G. Breckenridge/343
T. W. Hamilton/312

Bellcomm, Inc.

G. M. Anderson
D. J. Belz
A. P. Boysen, Jr.
J. O. Cappellari, Jr.
C. L. Davis
D. A. De Graaf
F. El-Baz
D. R. Hagner
W. G. Heffron
N. W. Hinners
W. W. Hough
B. T. Howard
D. B. James
J. Kranton
H. S. London
K. E. Martersteck
J. Z. Menard
G. T. Orrok
F. N. Schmidt
W. B. Thompson
J. W. Timko
J. E. Waldo
M. P. Wilson
All Members, Division 101
Central Files
Department 1024 Files
Library

Abstract Only to

Bellcomm, Inc.

I. M. Ross
R. L. Wagner